MECHANISMS FOR EXPLOSIVELY-FORMED FUSE PERFORMANCE DEGRADATION*

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Abstract

The Explosively-Formed Fuse (EFF) is a high-power opening switch that uses an explosive charge to interrupt current flow in an aluminum conductor [1]. As such we expected the foil's resistance to increase with increasing current density by Joule heating. Yet an analysis of a large number of experiments clearly showed the opposite was true; there was a strong negative correlation between the peak resistance and current density. In the paper we analyze various possible causes including thermal softening of the metal, magnetic loading of the explosive and electric breakdown or conduction in the product gases at the higher applied fields. Our analysis suggests that magnetic loading is responsible for the degradation.

I. INTRODUCTION

The Los Alamos National Laboratory EFF opening switch has been used extensively for a variety of high energy density physics applications [2][3][4][5]. In view of the importance of the switch we have invested considerable effort in its development to optimize its reliability and to control its performance [6][7][8].

In the course of development of the EFF switch for high voltage applications there was a noticeable and unexpected degradation in switch performance; the resistance was lower than predicted. Using cylindrical EFF switches of 10 cm diameter and 43 cm length, currents of approximately 3 MA were interrupted, producing ~200 kV. This indicates that the switch had an effective resistance of ~100 mΩ whereas 150-250 mΩ was expected. To understand the lower performance, and to optimize the performance of the full-scale experiments, several parameters were studied in a series of small-scale experiments. Eventually it was learned that the switch performance in the 10 cm diameter EFF was limited by explosive initiation problems peculiar to the 10 cm assembly, and these were successfully corrected. However, that was not before the small-scale tests were performed and some interesting results obtained. Of the many aspects of the switch that were studied, this paper focuses on identifying the possible mechanisms for performance degradation.

II. EXPERIMENTAL ARRANGEMENT

Planar, rather than cylindrical, assemblies were fired for simplicity, and economy. These experiments were designed to match the electrical and physical conditions of the full-scale switches. The standard small scale planar EFF design comprises the Teflon die, the explosive drive system, the aluminum foil, return conductor and insulation; see Figure 1 for the explosive lens-driven system.

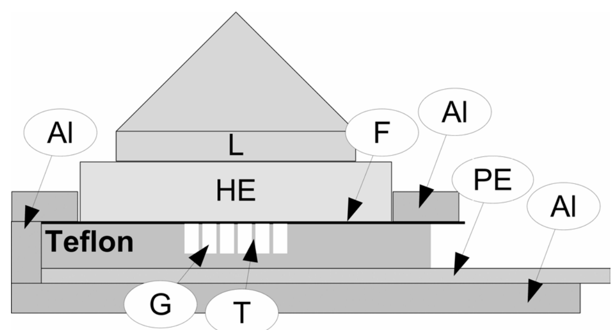

Figure 1. A typical small scale experiment with an explosive plane wave lens (L), the high explosive (HE), five teeth (T) in the Teflon die, six gaps (G), the aluminum conductors (Al), the conducting foil (F), and the polyethylene insulator (PE). The circuit electrodes are connected to the top and bottom aluminum conductors on the right.

The plastic die is a 19.05 x 165.1 x 165.1.mm (0.75 x 6.5 x 6.5 inches) Teflon block. A series of 12.7 mm deep, 6.0 mm wide grooves are cut across the block with a center to center spacing of 7.5 mm; this leaves a series of 1.5-mm wide Teflon teeth. In the early studies we used nine teeth, so there were ten grooves. Later on we realized that lateral rarefactions from the top edges of the explosive could encroach on the outside teeth in this design, so we reduced the number of grooves to six (i.e., five teeth).

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14. ABSTRACT
The Explosively-Formed Fuse (EFF) is a high-power opening switch that uses an explosive charge to interrupt current flow in an aluminum conductor [1]. As such we expected the foils resistance to increase with increasing current density by Joule heating. Yet an analysis of a large number of experiments clearly showed the opposite was true; there was a strong negative correlation between the peak resistance and current density. In the paper we analyze various possible causes including thermal softening of the metal, magnetic loading of the explosive and electric breakdown or conduction in the product gases at the higher applied fields. Our analysis suggests that magnetic loading is responsible for the degradation.

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The conductor is a 6.35-cm (2.5-in.) wide, 812.8-μm (0.032 in.) thick 6061-T6 aluminum foil. (Other metals have also been studied; moreover we have found that the switch performance of 6061 aluminum is sensitive to metal temper [9].)

The explosive lens-driven system uses a 100-mm diameter lens to initiate a 1-in. thick, 5.2-in. square slab of PBX-9501. We have also used an alternative tile-driven system, not shown, which uses a multipoint initiation plate to distribute a matrix of detonation points across its surface instead of a lens. The performance was more erratic with this tile system, probably due to breakdown through the plastics employed in the tile assembly.

The effects of many design variations have been studied including: the explosive type; the aluminum thickness; the current density; the addition of Teflon between the explosive and the aluminum; the type of die plastic; the cavity-depth in the plastic die; the surface finish of the plastic; and the load inductance. In this paper we only discuss the effects of changing the current density on switch performance.

III. RESULTS

We will refer to a number of features in the resistance profile here, in particular first motion, the knee, and the peak; see Figure 2. The actual values of resistance depend on the scale of the switch, but the time scale is constant and these basic features are always present.

First motion is the time when the shock wave from the detonating explosive arrives at the interface between

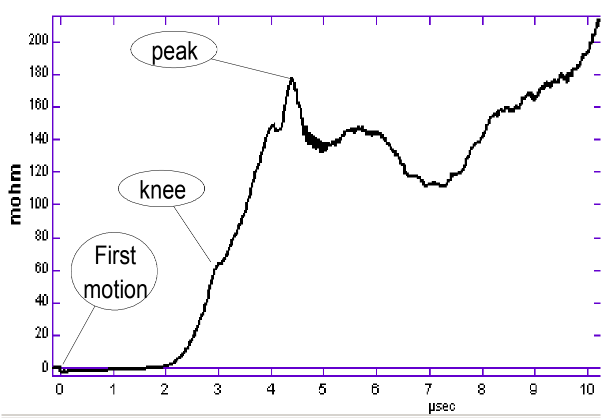

Figure 2. Typical features of a resistance waveform. The time is in μs and the resistance is in mohm.

the aluminum foil and the plastic die and the aluminum foil starts to move. It is characterized by a negative step on the resistance plot caused by reduction of the inductance under explosive compression; the time axes of resistance plots are normalized to first motion. Following first motion the resistance stays small for typically 2 μs, the rises towards the *knee*; this is a saddle point in the resistance rise and typically occurs 3 μs after first motion. The structure of the resistance rise from the knee to the peak determines the shape of the voltage profile across the switch I an inductive circuit [10]. The *peak* is the maximum resistance of the switch before the resistance falls; it usually occurs about 4.5 μs after first motion.

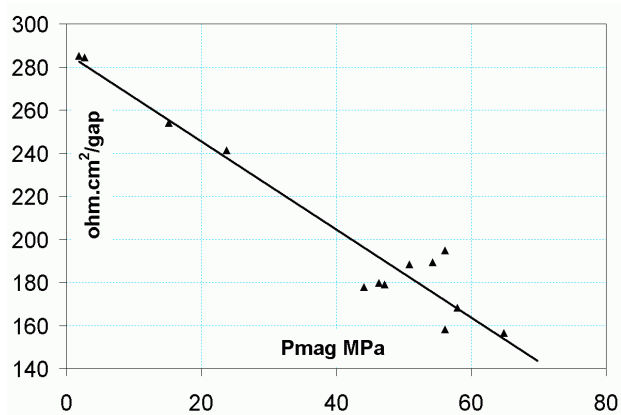

Figure 3. Plot of peak resistivity in ohm.cm^2/gap vs. calculated peak magnetic pressure in MPa.

In an effort to identify the electrical properties that control EFF performance we plotted various parameters including: peak resistivity; knee resistivity; time for resistance to rise to 10% of the resistance peak; and voltage developed per gap as abscissas against a range of different ordinates. These performance abscissas were plotted as scaled functions of many ordinates (scaled according to foil volume or width) including: peak current density; peak magnetic pressure; available energy in the circuit; energy dissipated; action integral; and available flux in the circuit [9]. Of all these, only good correlations were obtained between peak resistivity data in explosive lens driven systems and magnetic pressure P_b (Figure 3) or current density (Figure 4) as ordinates. (We plotted magnetic pressure but could just as easily have plotted current

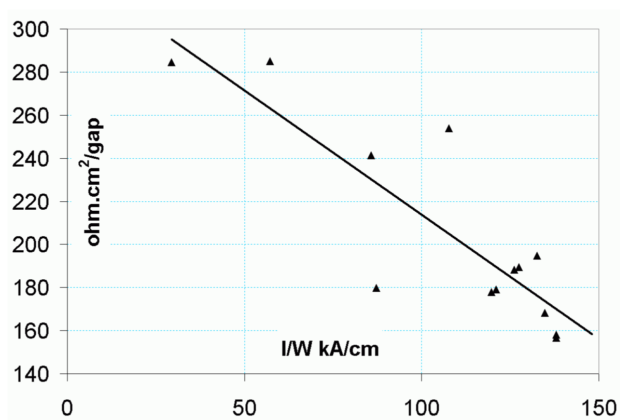

Figure 4. Plot of peak resistivity in ohm.cm^2/gap vs. peak current density (I/W) in kA per cm-width of foil.

density squared.) Here the calculated magnetic pressure was not corrected for the geometry of the EFF electrodes and the return conductors; it was simply defined as $P_b = \frac{\mu_0}{2}\left(I/W\right)^2$ where μ_0 is the permeability of free space

($4\pi\times10^{-7}$) and I is the current through the EFF. All data presented here are for the standard planar EFF design, i.e., a 1.5 x 6.0 x 12.7 mm tooth pattern; a Teflon die; a 6.35-cm wide x 32 mil thick 6061-T6 aluminum conductor; and an explosive lens system.

In Figures 3 and 4 the resistances are normalized as R′, the resistance in ohm.cm^2/gap, where $R' = (R\times W)\div(N+1)$, the conductor width is W and the number of teeth is N. As can be seen, the correlation of Figure 3 is the better of the two.

IV. DISCUSSION

The inverse correlations of EFF peak resistivity with current density (I/W) or $(I/W)^2$ shown above begged the question of what mechanism degrades EFF performance. Candidates we considered included thermal softening of the metal due to Joule heating; magnetic dead-pressing of the explosive; electric breakdown; and conduction in the product gases of the explosives.

A. Joule heating

In a typical small scale experiment the current rises to a peak according to the LCR resonance of the circuit, and the EFF is opened at the time of the first peak; i.e., after approximately a quarter cycle. The foil temperature rise due to Joule heating was not thought to be a candidate for a degradation of performance because the calculated rise is relatively small. For example, for the standard peak current density of 79 kA/cm, a 32-mil thick 6061-T6 aluminum foil, and assuming a room temperature of 300K (27°C), the foil temperature rises to 50°C for a current density rising sinusoidally to a peak in 35 μs.

B. Shock heating

By comparison, we have calculated that the direct contact with the detonating explosive shocks the aluminum to 35 GPa, followed by an adiabatic release to ~1 GPa as the aluminum is projected into the air cavity between the teeth of the Teflon die. The mechanical work done on the aluminum by shock compression raises the temperature to 550°C and the subsequent release causes the temperature to fall to 260°C [11]. (Further heating of the aluminum occurs during plastic deformation as it is extruded and thinned around the Teflon teeth.) So the effects of Joule heating are relatively small in comparison to shock heating and mechanical deformation.

C. Explosives conduction

It is known that the product gases of detonating PBX-9501 explosive are electrically conductive [12]; the electrical conductivity is estimated to be <1 S/m at the time the EFF reaches peak conductivity. The temperature of the gases is of the order of 3000K to 5000K, i.e., two orders of magnitude greater than the estimated temperature due to Joule heating. So, although the explosives' gases will reduce the peak resistivity of the EFF, the explosives resistivity will be little affected by changes in current density. We therefore discount this as the degradation mechanism.

D. Electrical breakdown

We doubt that this is the mechanism of degradation because the reduction of resistivity is a monotonic function of current density, as in Figs. 3 and 4, whereas electrical breakdown is usually a catastrophic event and would therefore cause an abrupt change in these curves.

E. Magnetic Dead-pressing

The magnetic pressure due to current flowing in the aluminum foil exerts a pressure upwards against the explosive shown in Figure 1. If the current density is large enough it can compress the explosive, by eliminating the voids within it, and reduce its sensitivity to the point that it may not initiate. This is termed dead-pressing [13] and in this case depends on the current density and the strain rate. The current density determines the applied magnetic pressure to the sample, and the strain rate dependence is due to the fact that an explosive's compressive modulus and strength are functions of strain rate.

We can estimate the maximum strain rate $\dot{\varepsilon}$ in a typical small scale (planar) experiment if we make the simplifying assumptions that the compressive modulus G is a constant, and that the relief waves reflecting back from a free surface are sufficiently delayed that they have little effect (see below) $\dot{\varepsilon} \approx \frac{1}{P}\frac{\partial P}{\partial t}$. Again, if the current rises sinusoidally to a peak in a quarter cycle period of 35 μs the total period T = 140 μs. The pressure varies as the sine^2, so the maximum fractional rate of change of pressure is $\frac{1}{P}\frac{\partial P}{\partial t} = \frac{2\pi}{T}$, which equates to $45\ \text{x}10^3\ \text{s}^{-1}$. From these data we can estimate the strength of the explosive.

In an actual small scale planar system the upper surface of the explosive is a free surface and rarefactions limit the compression across the sample and hence the strain rate. A 50 mm thick explosive package is typical for a small scale system and the longitudinal wave velocity in the explosive (PBX-9501) is 2.8 km/s. So the roundtrip transit time from the aluminum foil to the free surface and back again is 36 μs. This is close to the risetime of the sinusoidal current in the foil.

Initially the explosive is adiabatically compressed by the B-field according to the wave impedance of the explosive (Z). The explosive mass moves at the particle velocity u under the action of the magnetic pressure P_B, where $u = P_B/Z$, Eventually, upon arrival of the rarefaction wave after 36 μs, the explosive and aluminum separate *en masse* from the Teflon block under the action of the B-field. The maximum strain rate is likely to be somewhat less than $45\text{x}10^3\ \text{s}^{-1}$ because of these relief waves but still significantly higher than the strain rates for which we have good mechanical data.

The compressive modulus and strength of an explosive are strong functions of the strain rate; the explosive stiffens with increasing strain rate [14]. The compressive

strength of PBX-9501 is ~60 MPa (~69 ksi) at $3x10^3$ s^{-1} (the largest strain rate cited for PBX-9501 in the reference), and the maximum strain is ~1%. The true explosive strength under the influence of the B-field at $4.5x10^4$ s^{-1} will be higher, as will the compressive modulus; hence the strain will be lower.

In a typical small scale experiment the current peak is 500 kA which corresponds to a current density of 79 kA/cm in a 6.35-cm width, the magnetic pressure applied by the aluminum foil to the explosive is then ~39 MPa. As this applied pressure is less than the compressive strength the explosive will compress elastically. We can estimate a compressive strain of ~0.5% from [14]. A typical PBX-9501 explosive charge is pressed to a density of 1840 kg/m^3 compared with its theoretical maximum density of 1855 kg/m^3; it therefore has a pore volume of just 0.8%. Consequently, a 0.5% compression will actually reduce the void volume by 62% to just 0.3% which can dramatically reduce the sensitivity of the explosive [13].

F. Likely conditions for switch failure

From the plots of resistance versus pressure (Figure 3) we predict that the switch fails to open (the resistance goes to zero) at a maximum stress of ~140 MPa or 150 kA/cm, and this has been confirmed by experiments performed at that current density. From [14] we know that 140 MPa likely exceeds the strength of the explosive at any strain rate and the explosive will be compressed to zero porosity, i.e., to 1855 kg/m^3. This elimination of explosive voids will prevent detonation, i.e., it will dead-press the explosive. Consequently, the region of the explosive next to the aluminum will become an inert mass and impede the projection of the aluminum into the cavity.

V. SUMMARY

In the course of development of the EFF switch for high voltage applications there was a noticeable and unexpected degradation in switch performance at high current densities; the resistance was lower than predicted. The results of a parametric study of small scale experimental data confirmed that there are inverse correlations of EFF peak resistivity with current density (I/W) or $(I/W)^2$. To explain this we considered various candidate mechanisms including: thermal softening of the EFF conducting foil due to Joule heating; magnetic dead-pressing of the explosive; electric breakdown across the switch; and electrical conduction in the explosives' product gases.

Of these degradation mechanisms magnetic dead-pressing is the most likely; the voids of the explosive driver are compressed by the magnetic load to the point where the explosive cannot detonate.

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